Second United Nations
International Conference
on the Peaceful Uses of
Atomic Energy

A/CONF.15/P/2157
U.S.A.
June 1958

ORIGINAL: ENGLISH

DESIGN AND OPERATION OF A 10,000 GPM D. C. ELECTROMAGNETIC SODIUM PUMP AND 250,000 AMPERE HOMOPOLAR GENERATOR

R. A. Jaross and A. H. Barnes*

D. C. electromagnetic pumps and their related power supplies have been under investigation at Argonne National Laboratory since 1947. During this time approximately 30 different pump designs have been employed ranging from 5 to 10,000 gpm in capacity. This work has culminated in the design and construction of a 10,000 gal/min sodium pump and homopolar generator to supply its 250,000 amp current requirement. This pump-power supply combination, as constructed, features a compact unit aligned vertically so as to reduce the electrical conductor length between generator and pump and minimize the horizontal cross-sectional area. As originally conceived the unit was to have served as a prototype for the primary sodium coolant pump of the Experimental Breeder Reactor II. Figure 1 shows the unit without the vertical drive motor in place over the generator. With motor the entire structure is 30 ft high and weighs 35 tons. This paper will outline the important design features, discuss their merits and present initial tests results. The pump and generator will be discussed separately.

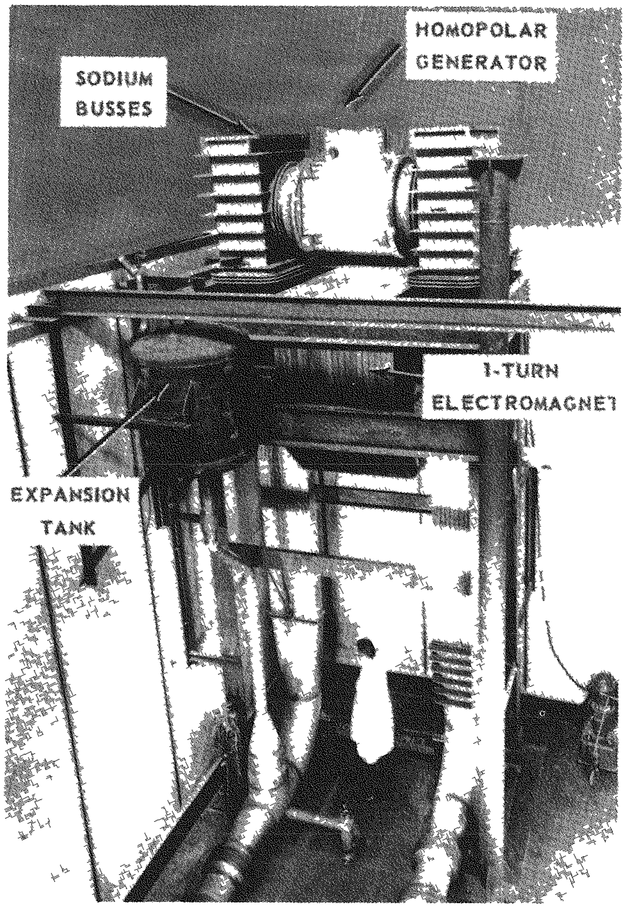


Fig. 1. Pump-Power Supply Unit.

*Argonne National Laboratory, Lemont, Illinois, U.S.A.

10,000 GPM SODIUM PUMP

A. Electrical Junctions

The principal advantage of the D.C. electromagnetic pump is its ability to operate in highly radioactive regions at very high temperatures. To achieve high temperature operation it is necessary that all electrical junctions in the pump be designed so as not to deteriorate. Conventional soldering and brazing methods are not adequate for high temperature applications. In selecting a material for use as the current conducting medium, a limited selection is presented. Low electrical resistivity is of paramount importance, however, some consideration must be given to the problem of joining the conductor to the pump duct. The choice of materials is limited generally to either copper, aluminum, silver, nickel, sodium or NaK. Most pumps built at Argonne use either copper, sodium, NaK or combinations of these. If space considerations are unimportant the use of sodium or NaK is very attractive since, when in its molten state, no thermal stress problems are encountered where electrical contact is made to the pump duct. This technique, in modified form, is used extensively in pumps built at Argonne. In the 10,000 gpm pump the bus from the current source to the pump consists of molten sodium contained in a long irregularly shaped box of rectangular section. Where space limitations are important, such as near the electromagnet of the pump, copper replaces most of the sodium. Where the actual electrical junction is made to the pump duct sodium is again used. Figure 2 illustrates this sodium to copper to sodium electrical conductor. It is possible with this conductor to avoid completely any welds of copper to stainless steel. In pumps where welds of this type are necessary a technique is used whereby intermediate welds of nickel and nickel-copper alloy are placed between the stainless steel and copper. This method is expensive and is to be avoided in large pumps.

B. Materials of Construction

In selecting the materials for use in the pump duct many considerations must be taken. The material most often used at Argonne is 18 Cr-8 Ni stainless steel. This material is chosen for the following reasons:

1. Good corrosion characteristics in sodium
2. High electrical resistivity
3. Good weldability
4. Non-magnetic
5. High temperature strength
6. Low Cost

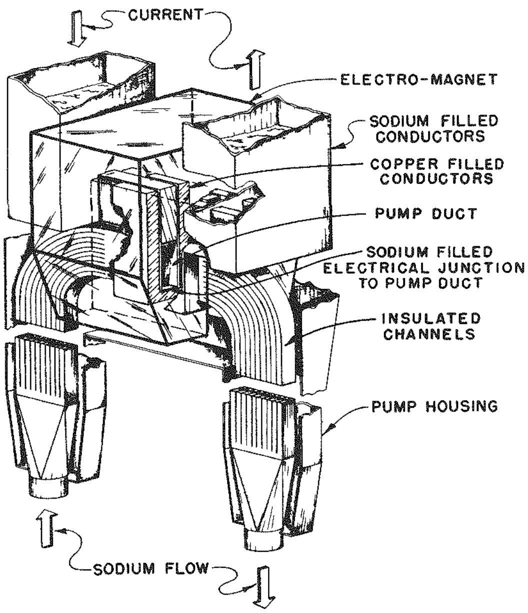


Fig. 2. 10, 000 gpm Sodium Pump Cutaway View.

Other materials surpass 18-8 stainless steel in one or more of these categories; however, experience has justified its use for the major portion of pump duct construction. At the actual region of current conduction across the pump duct a 1/16 in. thick sheet of 80% Ni-20% Cr alloy is used in the 10,000 gpm pump. The additional electrical resistivity gained by using this material is very important in this region.

In small DC-EM pumps built at Argonne commercial iron is used extensively for the electromagnet. The 16 ton electromagnet of the 10,000 gpm pump is low carbon steel. The poorer magnetic characteristics are offset by its lower cost.

C. Pump Duct and Electromagnet Construction

The pump duct in small pumps is formed into a rectangular section from a round tube. While inexpensive, strength and reliability are sacrificed since welding must now be done on the thin tube wall in order to attach the electrical conductor.

As pump sizes increase, another serious problem confronts the designer. The head-capacity relationship of the pump depends on the amount of current which actually traverses the pump duct in the region of strong magnetic field. In practice it is found a large portion of the current does bypass this region by traveling down the pump duct and crossing outside the magnetic field. This has the effect of making a very poor head-capacity relationship and consequently an inefficient pump. In order to avoid this bypassing loss the pump duct is divided into many separate channels, each insulated electrically from the other. The path the current must now take in order to bypass the high flux region is greatly lengthened and hence the amount of bypass current reduced.

The 10,000 gpm pump has 12 electrically insulated channels each $1\frac{5}{8}$ in. by 6 in. in flow cross-section. These channels are made entirely of 1/16 in. thick 18-8 stainless steel. The channels extend into the electromagnet gap for a distance of 6 in. at each side at which point the 12 channels are terminated into a single pump duct which measures $20\frac{7}{8}$ in. high, 6 in.

wide and 30 in. long. In this duct all pumping takes place. The 16 ton electromagnet is made up of 20 - 2 in. thick carbon steel plates with a 1/8 in. spacing between each. The magnet furnishes a flux density of 4000 gausses in the 15 in. air gap with 250,000 ampere-turns excitation.

D. Electrical Design Features

It has been found advisable to build DC-EM pumps with series excited electromagnets. This is especially true in larger pumps. As the current requirements of the pump increase, the flux density does not alter greatly , hence the ampere-turns needed for the electromagnet depends on the air gap size and ultimately the pump's capacity. The 10,000 gpm pump has a one-turn series excited electromagnet. While this design is not good from the standpoint of flux leakage, it is simple and inexpensive.

The use of large pumping current and a one-turn electromagnet necessitates the employment of some compensating device to overcome the cross-magnetizing magnetomotive force produced by the current in passing through the pump duct. Graded field poles and tapered pump ducts could be employed but for simplicity of design a series compensating turn is used. After traversing the pump duct the current immediately returns in an opposite direction through a path parallel to the pump duct current path. Since no magnetic material is linked by this turn, it cancels the cross-magnetizing effect of the pumping current. In Fig. 2 the compensating turn is two parallel conductors on each side of the pump duct.

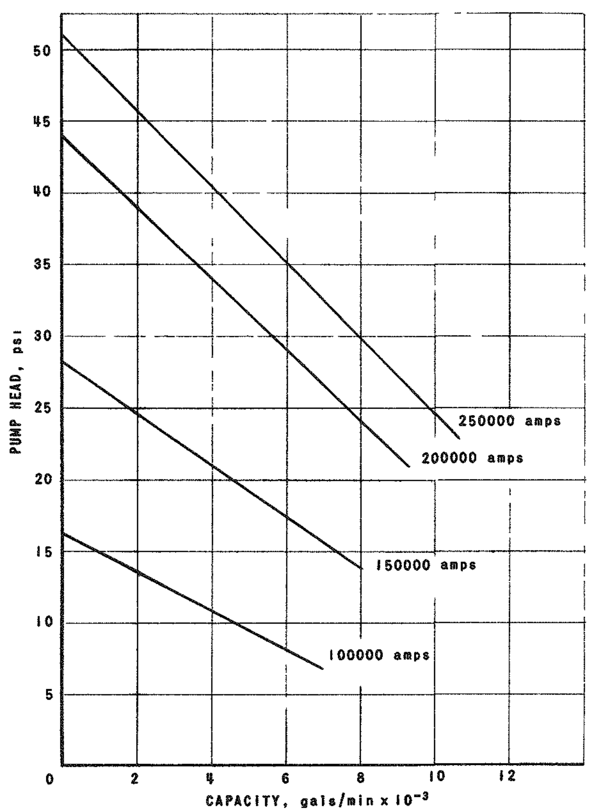


Fig. 3. Head-Capacity Relationship of 10, 000 gpm Pump in 700°F Sodium.

E. Test Results

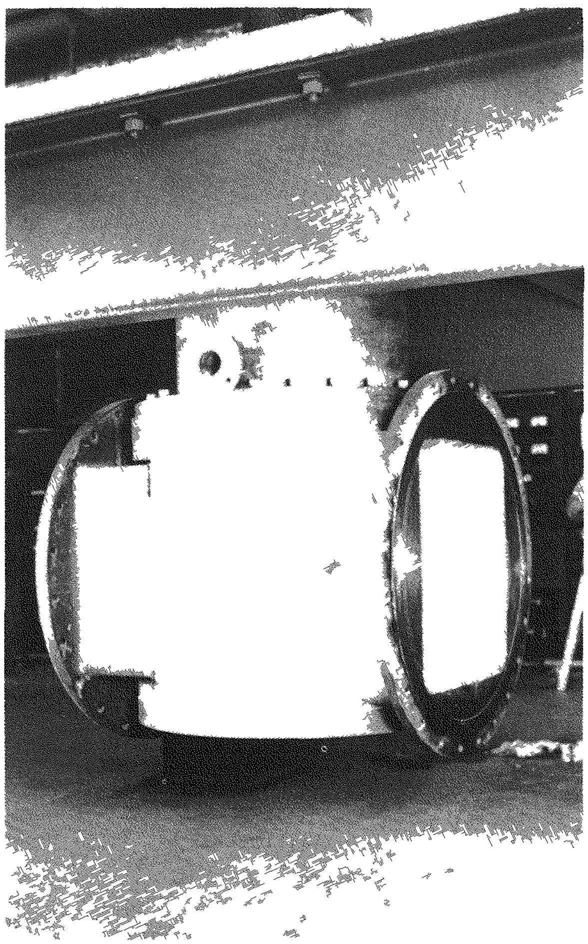
Initial test results on the pump have not been entirely satisfactory. Figure 3 shows the head-capacity relationship for the pump at various constant current input conditions. The steepness of the curves together with low shut-off pressure results in an inefficient pump (approximately 20% at 10,000 gpm). This can be attributed to two factors:

1. The leakage flux of the electromagnet is higher than anticipated, thus causing saturation of the steel magnet while the flux density in the air gap is still relatively low.

2. The fringing flux at the ends of the magnet cause eddy currents to circulate in the 12 insulated channels. Since very little by-passing current traverses the 12 channels, voltages are induced in the sodium as it moves through the fringing flux field. In each channel these voltages produce eddy currents, the effect being a reduction of the over-all head of the pump.

By more carefully matching the fringing flux to the by-pass current it will be possible to greatly improve the pump's performance. Work on this phase is proceeding at present with conclusive results expected within three months.

HOMOPOLAR GENERATOR



As in the case of the direct current-electromagnetic pump, past work has culminated in the design and construction of a large liquid brush homopolar generator. This generator was designed and built specifically for use with the 10,000 gpm pump. The nominal rating of the generator is 250,000 amperes, three volts DC. Figure 4 shows the generator ready for installation over the 10,000 gpm DC-EM pump. The flanges shown are standard 30 in. diameter pipe flanges and serve as the electrical terminals for the generator. The sodium to copper to sodium electrical bus mentioned above makes its junction with the generator at this flange. Although the generator was designed for specific application with the 10,000 gpm pump, it could be easily adapted to conventional applications.

Fig. 4. 250,000 Ampere Homopolar Generator Ready for Installation.

A. General Design

In Fig. 5 a cut-away on the generator is shown with the vertical drive motor in place. There are no windings of any kind on the rotating armature of the generator, the 12 in. diameter rotor being composed of solid copper, iron and stainless steel cylindrical plugs as shown in Fig. 6.

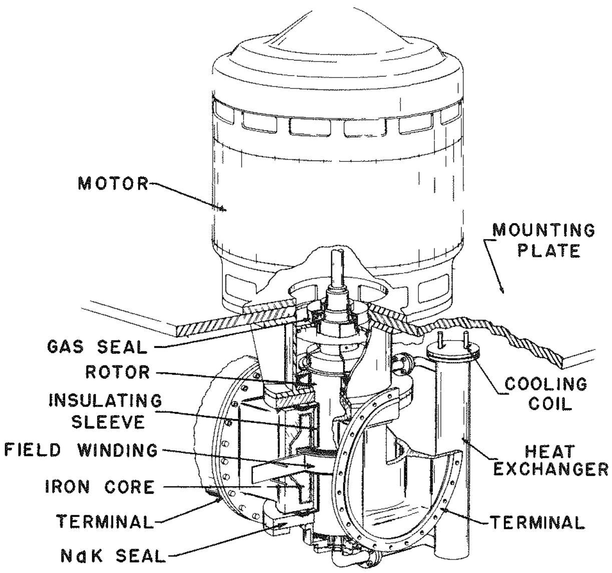


Fig. 5. Homopolar Generator Cutaway View.

The electrical design of the generator is basically very simple and well established. However, some of the design features used to improve efficiency and mechanical reliability are worthy of mention.

The generator is of the liquid brush type. Eutectic NaK serves as the current-conductor between the rotating and stationary members and covers the rotor completely. Were it not for an insulating sleeve a direct short circuit would exist at all points along the rotor, since NaK would be in contact with the stationary conductor at one potential and the rotor at another. This insulating sleeve could be a single stainless steel cylinder sealing the NaK from the stationary conductor, however the sleeve itself is a

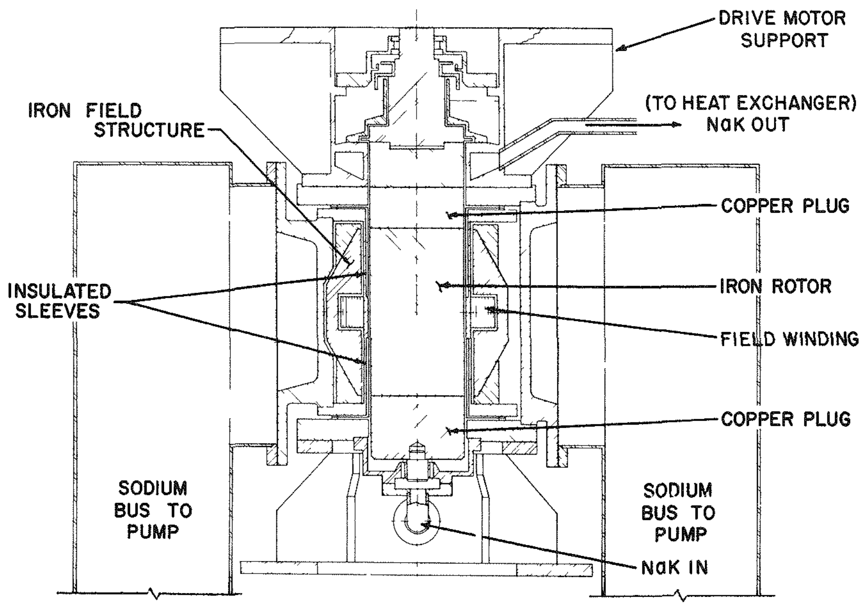


Fig. 6. Homopolar Generator Cross-Sectional View

short circuit path and must be very thin in order to reduce losses. The sleeve is composed of two concentric cylinders welded at one end and insulated from each other at all other points. The heavy outer cylinder carries no current and supports the thinner cylinder which is a short circuit path. The inner cylinder can be made quite thin (0.008 in.), thus limiting the short circuit losses. If any NaK leak or insulation breakdown occurs between these two cylinders a short will ensue which will be cumulative in nature resulting in a complete shutdown of the generator. The use of an insulated coating on the stationary conductor has been avoided since even the smallest pinhole could not be tolerated. For this reason a welded stainless steel cylinder is used.

The rotor of the generator could be entirely iron. Were this done, however, fringing flux would travel from stationary core to rotor across the 2 in. wide copper outer terminal ring. With NaK in contact with this ring a difference of potential would exist across it and very large currents would circulate in the ring. It is therefore important to generate all the voltage only in the iron portion of the rotor. The copper plugs in the rotor are silver soldered to the central iron plug to insure good electrical contact.

A chief concern in the design of homopolar generators has been their magnetic unbalance. This comes about because the rotor cannot, for practical purposes, be perfectly centered in the toroidal magnetic field. Any unbalance is cumulative and pulls the rotor in one direction radially. In conventional machines this unbalance is not serious because the bearings take the added load easily, but in a vertical homopolar almost all of the radial thrust must be taken by the top bearing which is located above the NaK level. This problem of magnetic unbalance is solved by two devices. First, the shaft from the rotor to the main radial bearing is very heavy, tapering from 12 in. diameter to $4\frac{1}{2}$ in. diameter in a length of 15 in. This very rigid member serves to hold the rotor centered even under very strong undirectional radial thrusts. Second, the magnetic unbalance itself is reduced by enlarging the air gap of the generator. The amount of radial thrust depends on the ratio of initial unbalance to air gap length. By keeping the air gap large the thrust is reduced. It would be possible to laminate the stationary inner current conductor with iron and reduce the ampere-turns required for the air gap. This shortening of the air gap would greatly increase the unbalanced force on the rotor, however.

The electrical losses of the generator are high per unit volume. This could cause a cooling problem were it not for the fact that the NaK brush is continually circulated through the machine and to an external NaK to water heat exchanger, the pumping power being provided by the turning rotor. All of the losses except excitation and bearing losses are removed in this manner. Operating at full load this amounts to approximately 60 KW. Since most of the losses, hydraulic and short circuit, are produced in the NaK itself, heat transfer is simplified in the generator. The maximum generator temperature can be maintained below 150°C with this cooling technique.

The excitation to the generator field is supplied by a separate source of 3000 amp DC. The field coil is composed of 13 turns of heavy copper strap, water-cooled. By using a dry rectifier to supply field excitation, the output voltage of the generator can easily be regulated to very small increments. This fact is important in DC-EM pump applications.

With so high a load current great care must be taken to avoid cross-magnetizing the field structure. This can easily be done in the stationary members by carrying the load current parallel to the rotor current and immediately adjacent to it. The only cross-magnetizing flux exists in the rotor iron and requires approximately 8000 amp turns additional excitation over that required for the air gap and iron alone. To date the highest load current carried by the generator has been 507,000 amp at 1.58 v, the field current required at this point being 2980 amp.

An inert gas blanket must be maintained over the NaK. In order to limit leakage of this gas, a shaft seal is located in this gas space. The gas seal is lubricated with a small amount of oil and continuous observation is made on the seal temperature while operating.

Past experience with NaK brush homopolar generators has shown that the principal problems have been the following:

(a) Cooling of the generator.

(b) Fringing flux causing circulating currents in terminal rings.

(c) Magnetic unbalance causing displacement of rotor.

(d) Leakage of NaK from generator.

These problems have been solved to the satisfaction of Argonne in present generator.

B. Test Results

Before installation of the generator over the pump, tests were made in order to establish its reliability and obtain necessary electrical data. The condensed results of these data are shown in Figs. 7 and 8. In these tests the electrical load on the generator was composed of many water-cooled copper tubes connected in parallel. The tubes were arranged so that the total

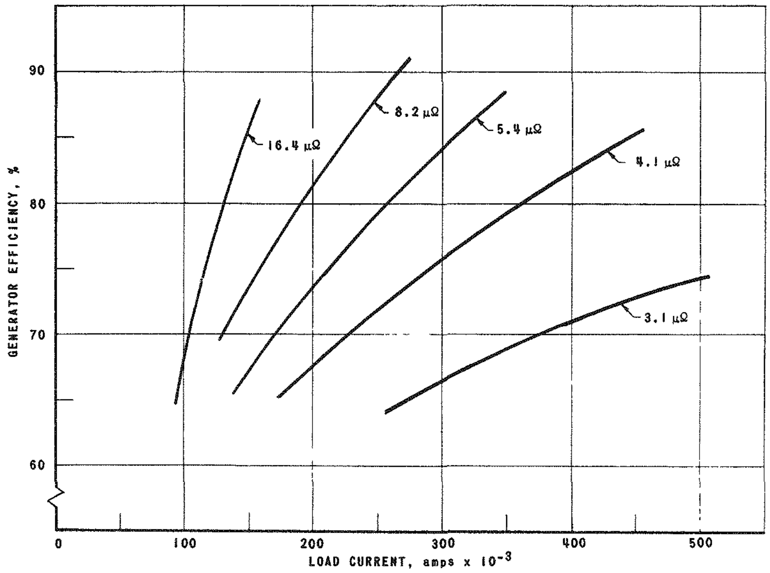


Fig. 7. Homopolar Generator Efficiency vs. Current at Constant Load Resistance.

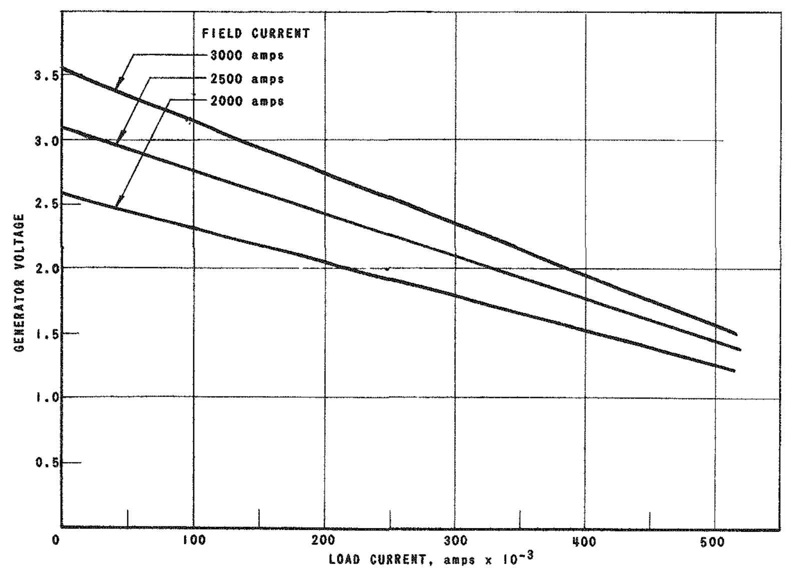


Fig. 8. Homopolar Generator Voltage vs. Current with Field Excitation Constant

load resistance could be varied from 3.1×10^{-6} ohms upward in several steps. It was unfortunately impossible to obtain maximum efficiency data due to the limited electrical capacity of the copper load tubes.

The homopolar generator has operated successfully for several hundred hr. on load tests and also in actual use with the 10,000 gpm pump. The combined pump-generator-drive motor unit has shown itself to be mechanically sound. The essence of the unit lies in its ability to convert 2300-v, 3 phase electrical power to controllable sodium pumping. The compact arrangement of the unit allows its movement in one piece. This feature, plus its small horizontal cross-section, makes this unit design applicable to the primary system of the EBR-II.

ACKNOWLEDGEMENT

All phases of design and construction of this pump-power supply unit were carried on under the direct supervision and personal guidance of the late Dr. Arthur H. Barnes. He performed the fundamental design work and directed the facilities of Argonne National Laboratory in the evolvement of the unit.

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